
Neutrinos Get
Under Your Skin!
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ΑΘΗΝΑ
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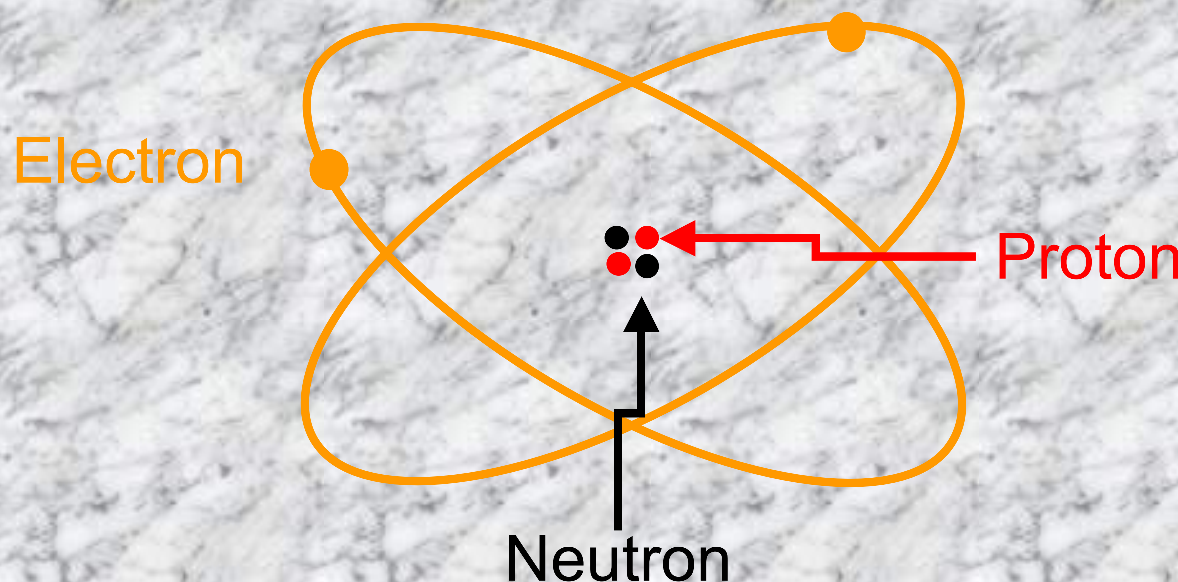
We, and all everyday objects, are made of 3 kinds of tiny particles:

Electrons Protons Neutrons

These are bundled together to make Atoms:



These atoms make up—

People —

Man-made structures—

Our home planet—

Is The Whole Universe made of—

Electrons Protons Neutrons ?

NO!

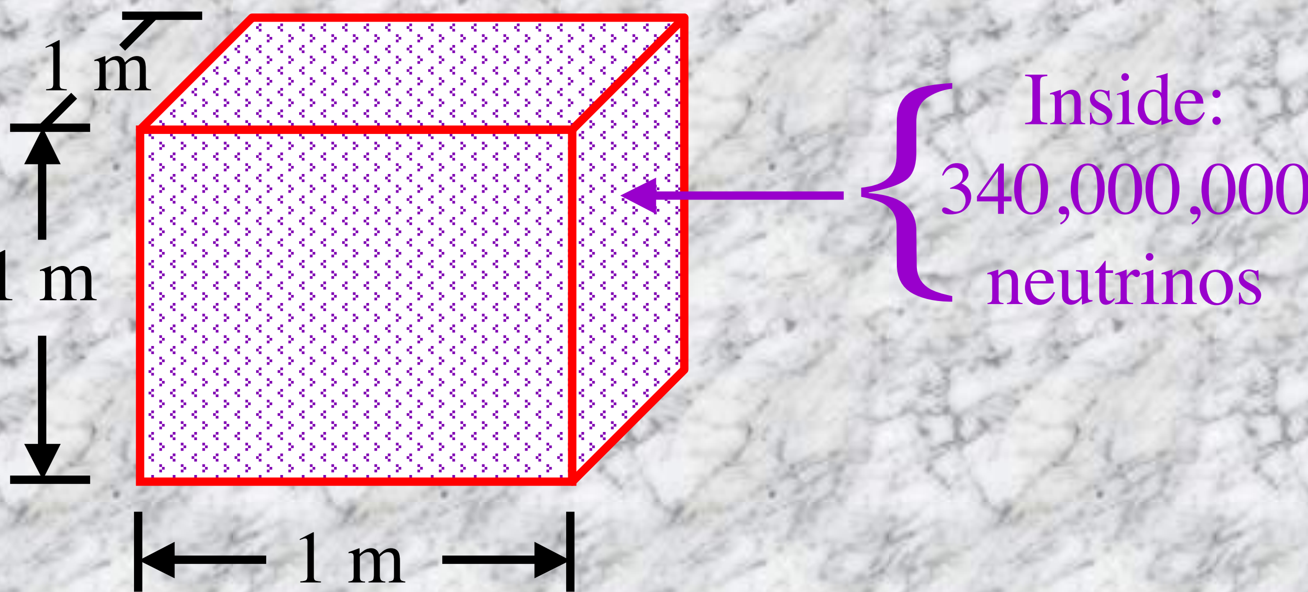
Electrons Protons Neutrons

are rareties!

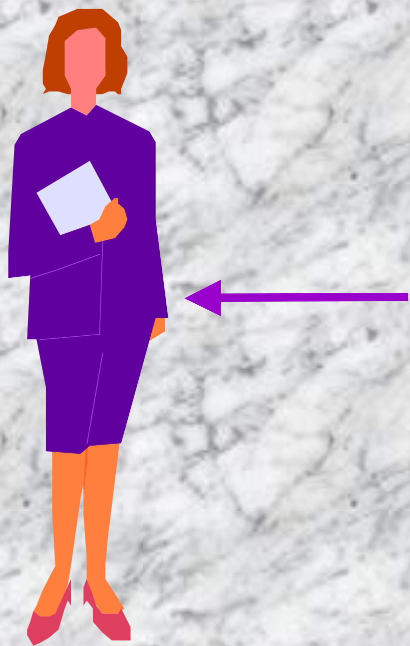
For every one of them, the universe contains a billion neutrinos ν!

To understand the universe, we must understand the neutrinos.

Within each cubic meter of space:
340 million neutrinos from the Big Bang.



Within each person:
Roughly 30 million Big Bang neutrinos



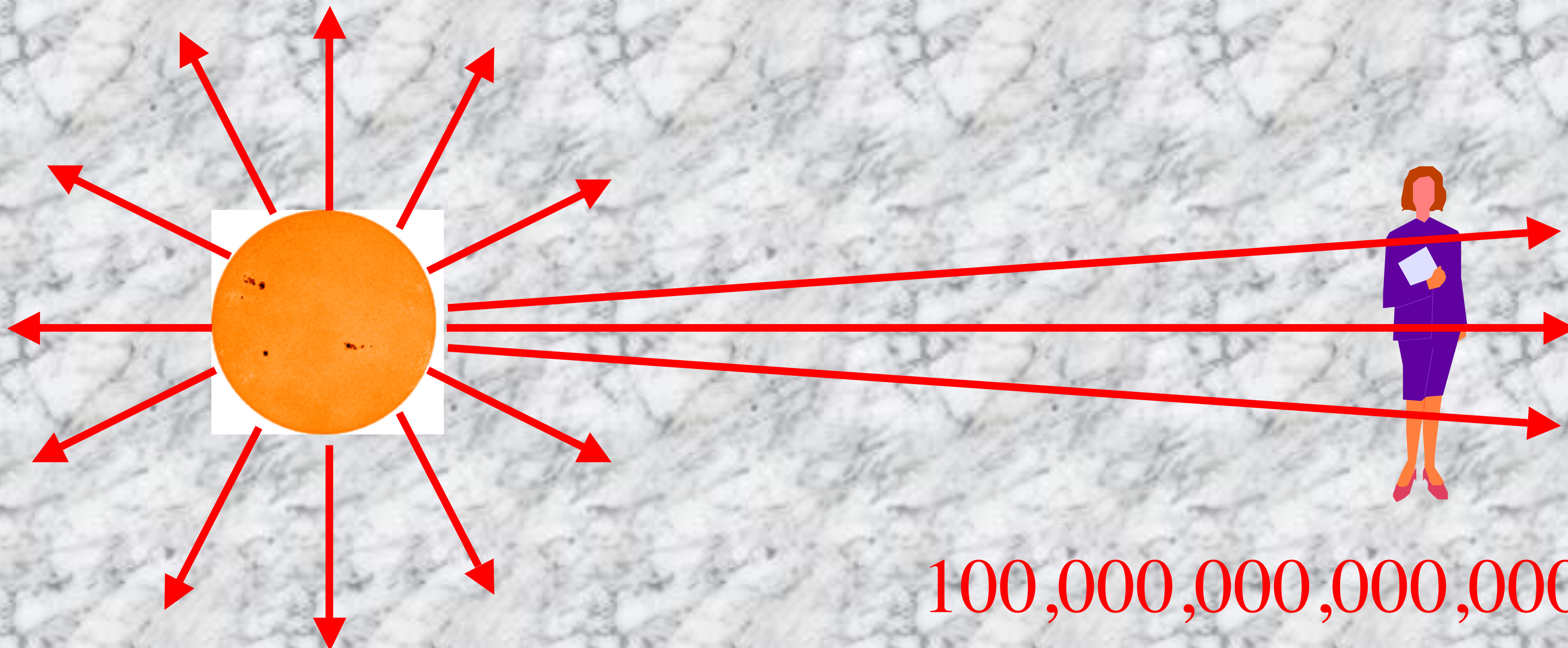
Inside:
30,000,000
neutrinos

Passing through each person on earth every second:
One hundred trillion neutrinos from the sun.

The sun shines because of nuclear fusion in its core.

This fusion produces—

- Energy, making life on earth possible
- Neutrinos



100,000,000,000,000

νs zip through each second.

Neutrinos–lots of them–get under your skin!

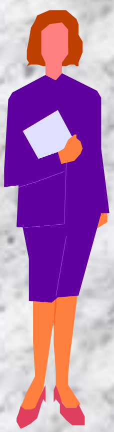
Should we worry about all those neutrinos zipping through us?

No. Neutrinos interact with other matter VERY FEEBLY.

To a neutrino, we look like almost completely EMPTY SPACE.

The neutrino is right — we ***are*** almost completely EMPTY SPACE.

Just like the solar system.

Our view 

 ν View

Almost all neutrinos zipping through us do nothing at all.

Typically, a solar neutrino would have to zip through 10,000,000,000,000,000,000 people before doing anything.

The probability that a particular solar neutrino will interact as it zips through one of us is 1 / 10,000,000,000,000,000,000 .

This same feebleness of interaction makes neutrinos hard to detect and study.

They are ghostlike.

Abundant but Elusive.

Are Neutrinos Important to Our Lives?

If there were no νs, the sun and stars would not shine.

- No energy from the sun to keep us warm.
- No atoms more complicated than hydrogen.
  No carbon. No oxygen. No water.
  No earth. No moon. No us.

They say that —

No *news* is *good* news.

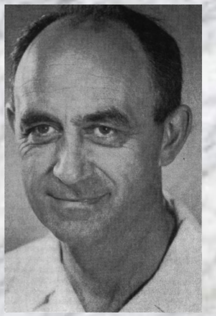
But —

No ν *s* would be very ***BAD*** news.

What Are Neutrinos?

neū·trï´nō: Little neutral object

Enrico Fermi



Q: How little are neutrinos?

A: Roughly 1/10,000,000,000,000,000 inch across. This is 1/1,000 the size of an atomic nucleus.

Q: How much do neutrinos weigh?

A: Almost nothing. Years of experiments yielded no evidence that neutrinos have any mass at all.

Q: Could neutrinos be *completely* massless?
Can a particle have *no* mass at all?

A: A particle *can* be a bundle of pure energy, and have no mass at all.

The photon—the particle of light—is like that.

But we have recently discovered that neutrinos are *not* like that.

Neutrinos weigh much less than electrons, protons, or neutrons, but they *do* have tiny nonzero masses.

Q: How do we know neutrinos have masses?

A: We'll explain that shortly.

Q: Are all neutrinos the same, or are there different kinds of neutrinos?

A: Neutrinos come in three different flavors:

The electron neutrino	ν_e	Vanilla
The muon neutrino	ν_μ	Chocolate
The tau neutrino	ν_τ	Strawberry

Q: How do ν_e, ν_μ, and ν_τ differ from one another?

A: All the particles of a given kind are identical.
All electrons are absolutely identical.
Electrons do not have birthmarks.

But there are 3 kinds, or flavors, of electron-like particles:

Particle	Symbol	Mass	Associated Neutrino
Electron	e	1	ν_e
Muon	μ	200	ν_μ
Tau	τ	3500	ν_τ

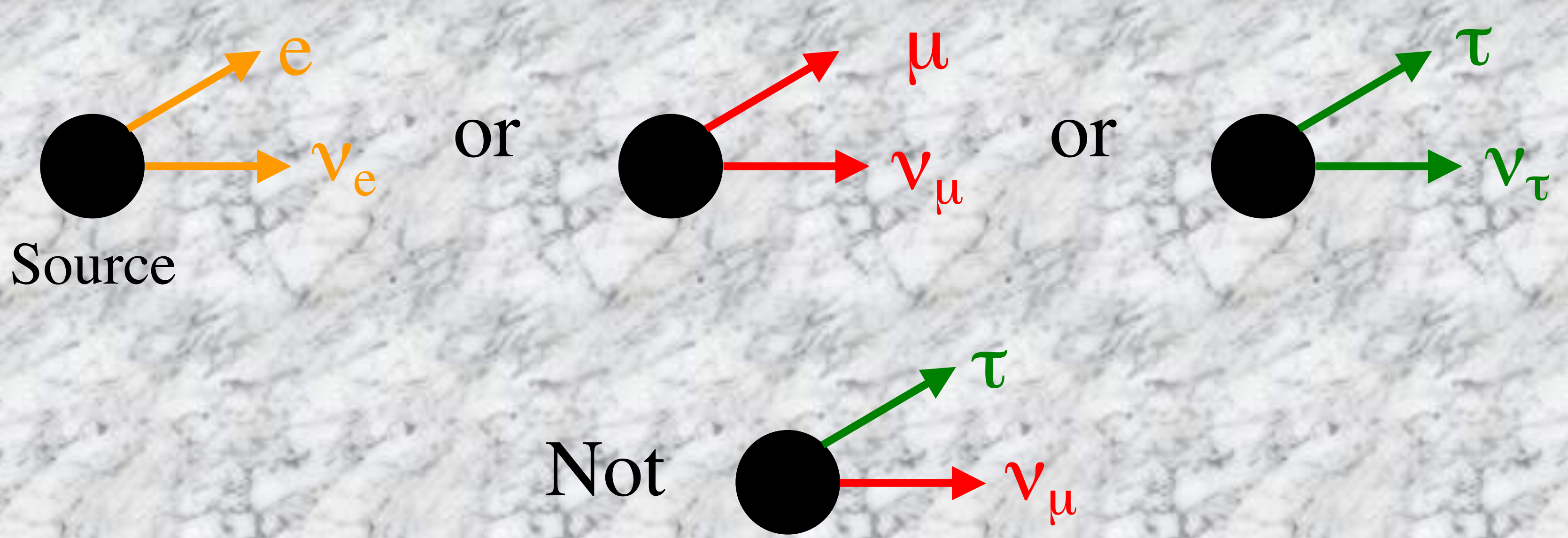
e, μ, and τ are electrically charged, and are known as the charged leptons.

(Physicists use a lot of Greek!)

Neutrinos are created in a variety of physical processes.

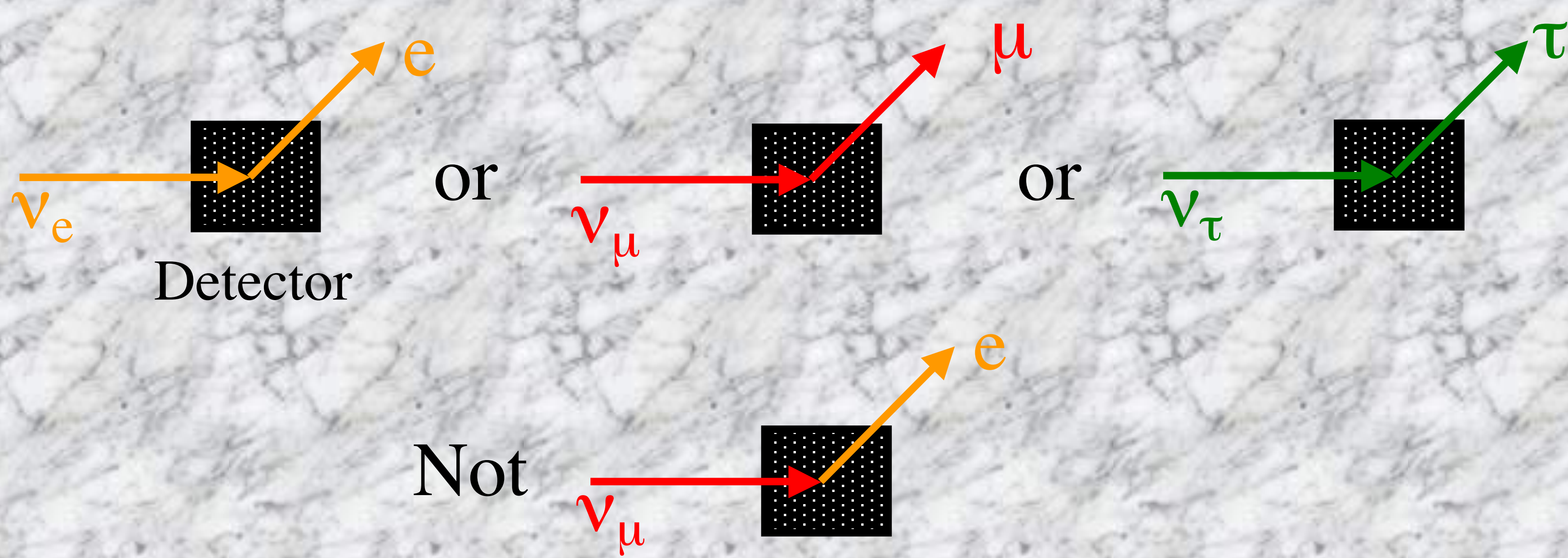
In nature or the laboratory, a neutrino is created together with a charged lepton.

The neutrino and charged lepton always have the same flavor.

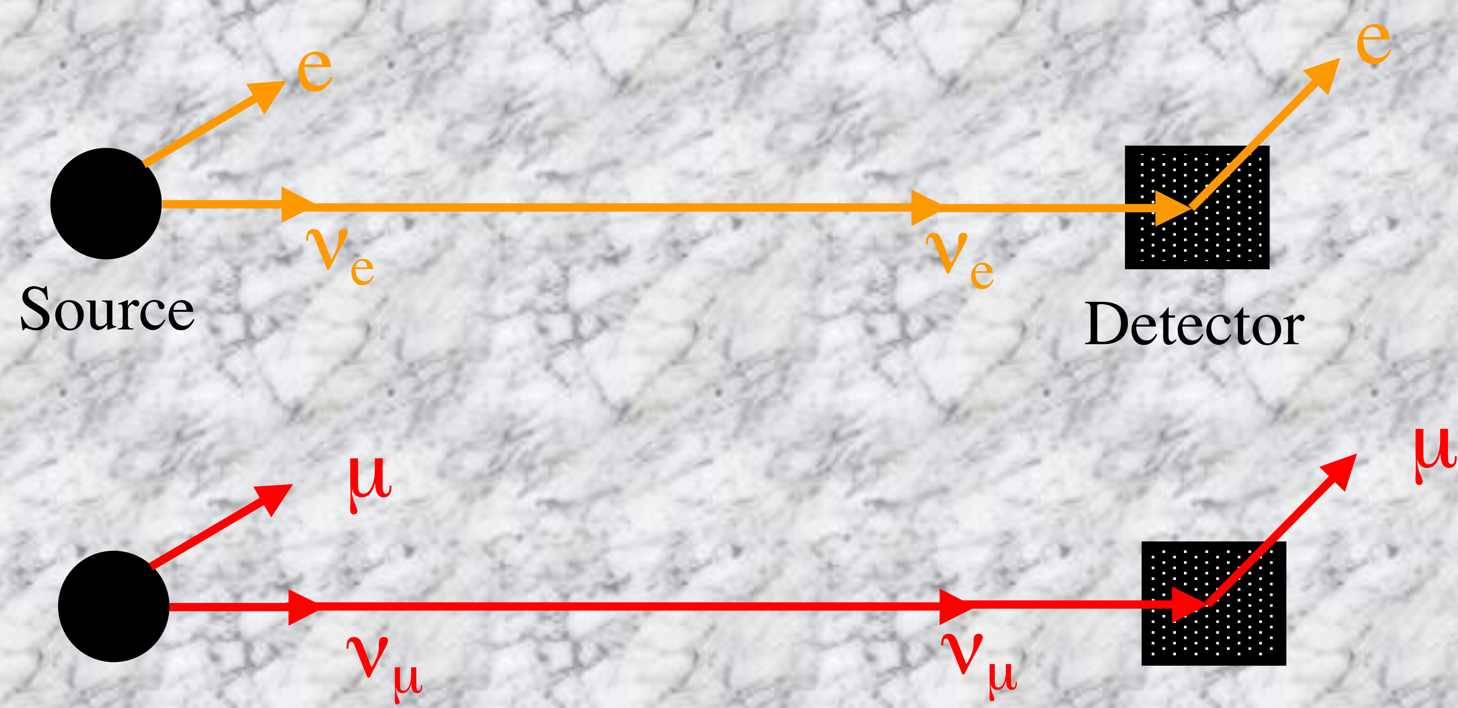


When a neutrino collides with an atom in a neutrino detector, it creates a charged lepton.

The charged lepton always has the same flavor as the neutrino.



Creation and Detection of a Neutrino



Flavors don't mix.

Neutrino Flavor Change and Neutrino Mass

Neutrino masses, though nonzero, are still tiny compared to the masses of other particles.

How did we detect such tiny masses?

Suppose neutrinos do have nonzero masses…

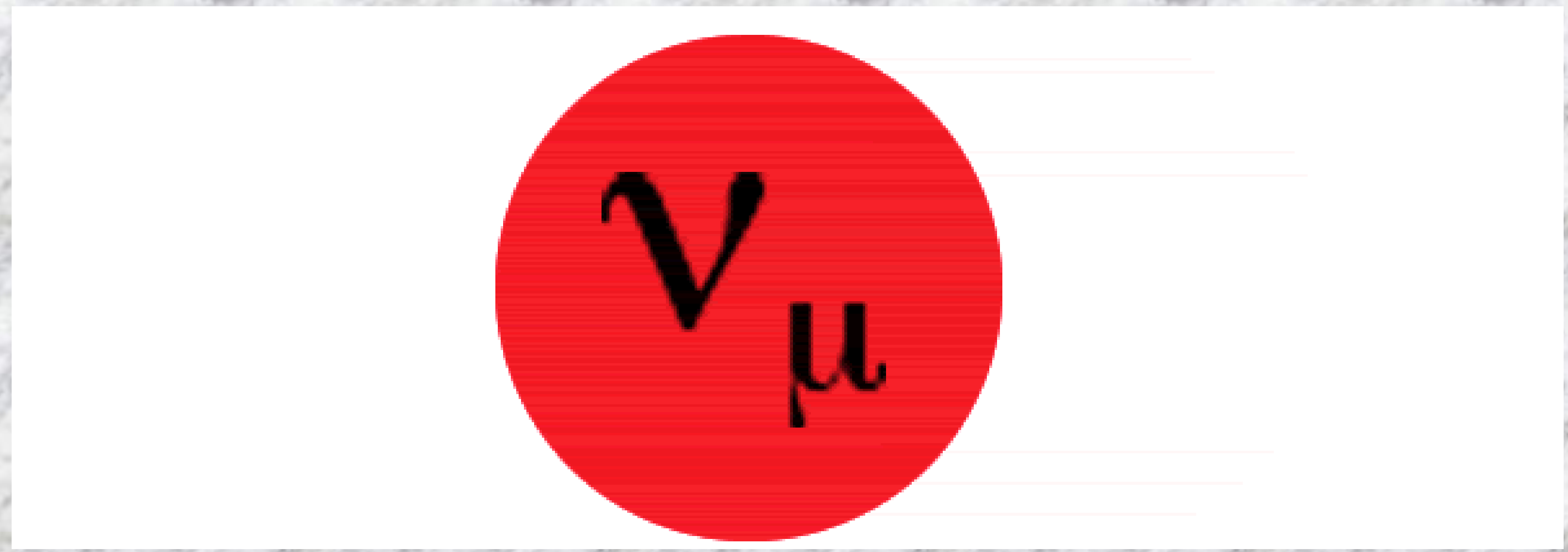
Then, if you give a neutrino enough time, it can change from one flavor to another!

The neutrino oscillates between two flavors:

Born ν_μ → Maybe ν_μ Maybe ν_τ → Pure ν_τ → Maybe ν_μ Maybe ν_τ → Pure ν_μ →

Time, or Distance Traveled

Neutrino Oscillation



The world of the tiny particles is governed by QUANTUM MECHANICS.

Quantum mechanics involves *uncertainty* at its core.

An object can be maybe here and maybe there.
It can be maybe this and maybe that.
It can be maybe a ν_μ and maybe a ν_τ.

A proton is a proton is a proton.
It does not change, all by itself,
into something else.

How does a ν_μ change into a ν_τ ?
Answer: A ν_μ is not a particle to begin with.

Different masses

There *are* neutrino particles: $\overbrace{\nu_1, \quad \nu_2, \text{ and } \nu_3}$.

Also known as:


Tom

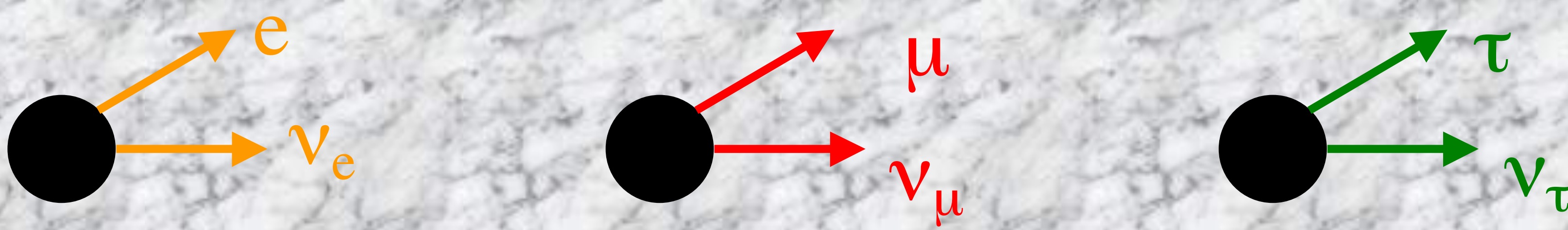

Dick


Harry

(Thanks: R. Chast)

ν_e, ν_μ, and ν_τ are different MIXTURES of ν_1, ν_2, and ν_3.

In each of—



the emitted neutrino is actually a ν_1, ν_2, or ν_3.

ν_e is:

maybe ν_1
maybe ν_2
maybe ν_3

ν_e, ν_μ, and ν_τ are different soups, all made from the same ingredients: ν_1, ν_2, and ν_3.

Voyage of a Neutrino

Original ν_1, ν_2, ν_3 Soup

ν_1, ν_2, ν_3 parts of soup travel at different speeds because they have different masses.

New, different ν_1, ν_2, ν_3 Soup

The ν_μ mixture of ν_1, ν_2, ν_3 has turned into the ν_τ mixture.
But only because ν_1, ν_2, ν_3 have different masses.

Neutrino flavor change implies neutrino mass!

Neutrino flavor change

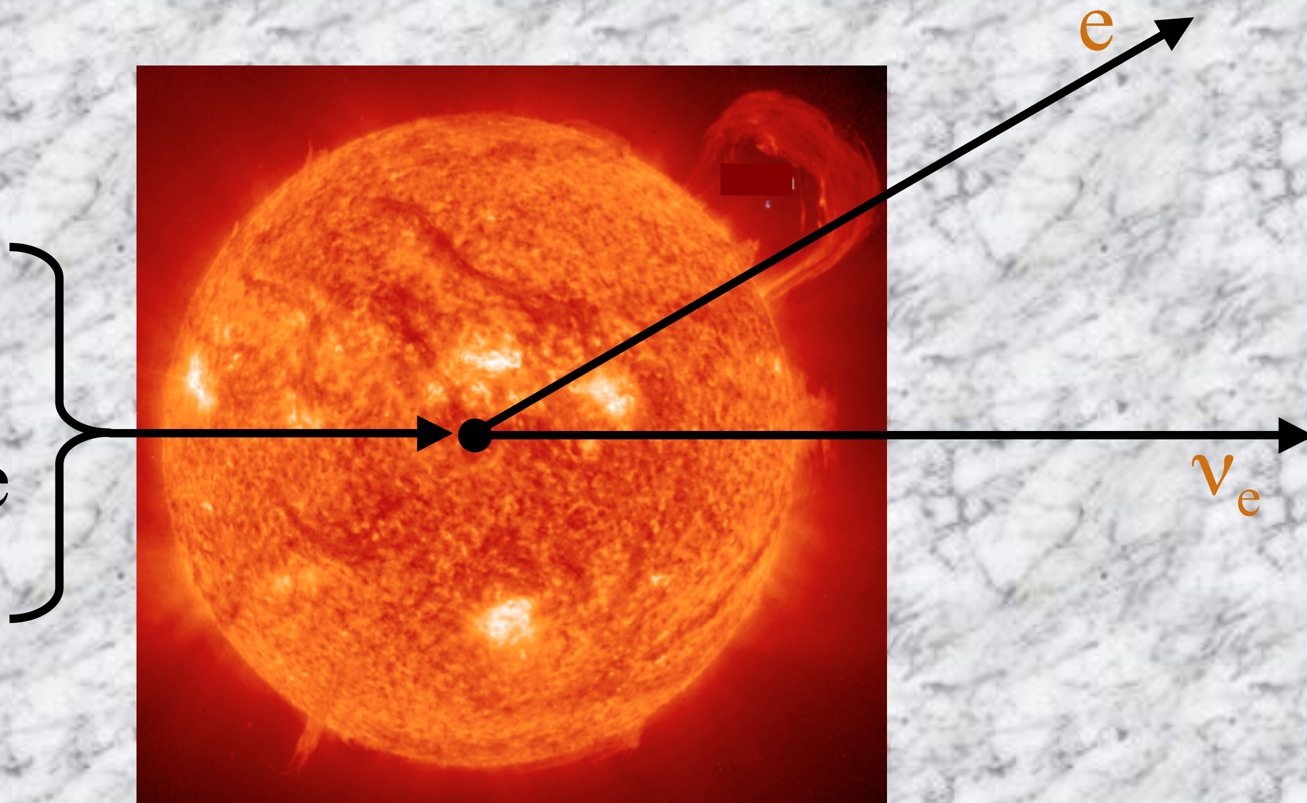
("neutrino flavor oscillation")

can make even *tiny* neutrino masses visible

if we let the neutrinos travel far enough.

One Example of the Evidence for Neutrino Flavor Change

Nuclear reactions in the core of the sun



Solar neutrinos are all born as ν_e , not ν_μ or ν_τ .

John Bahcall

Theoretical astrophysicist
Calculated how many
ν_e the Sun produces

Ray Davis

Experimental chemist
Counted how many
ν_e arrive at Earth

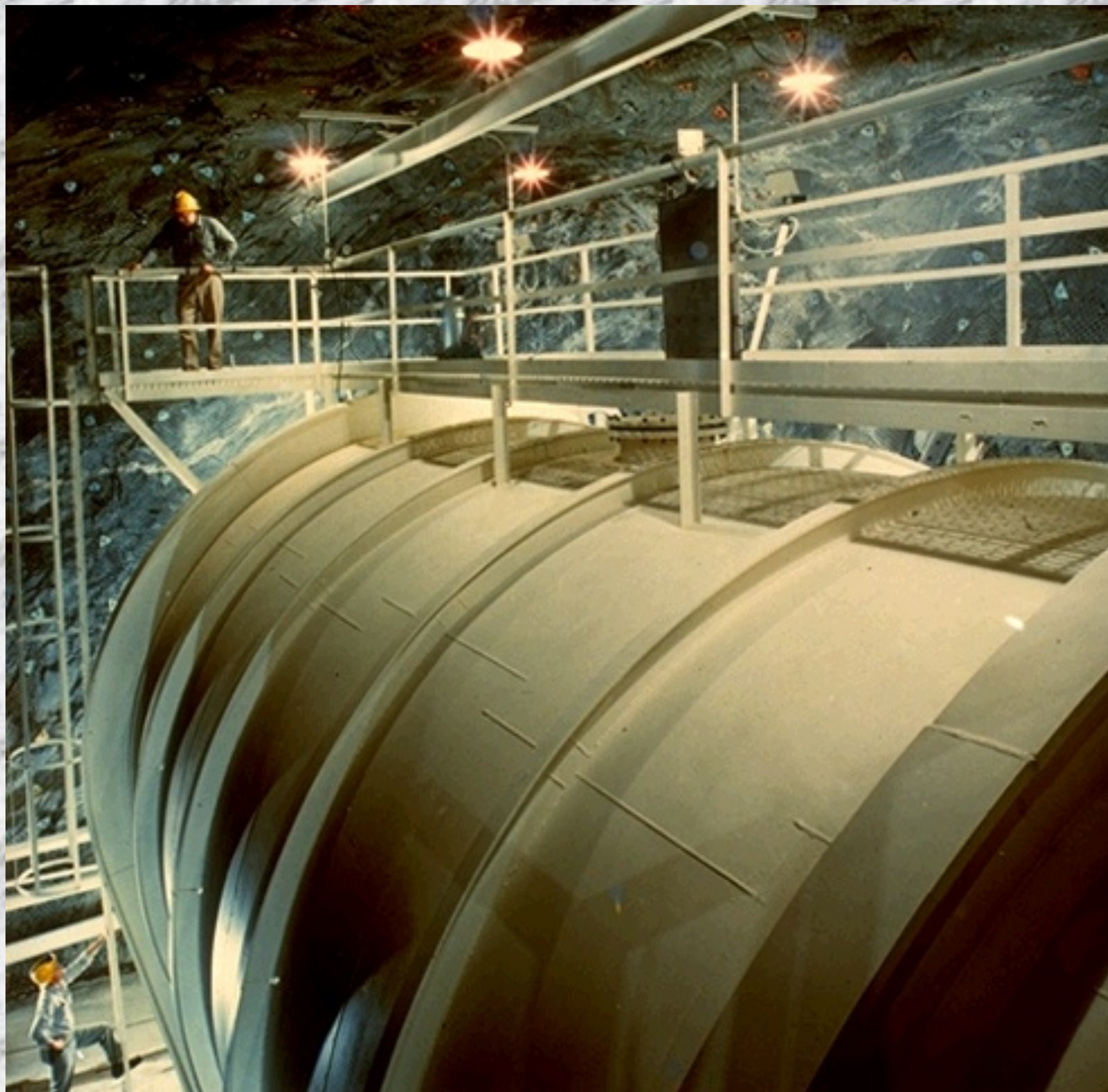
To detect the solar neutrinos arriving at the earth, we go deep underground.

Protons and heavier particles are raining down on earth's atmosphere from outer space.

These incoming particles are called cosmic rays.

In a neutrino detector, cosmic ray "events" can imitate neutrino events.

To eliminate the cosmic ray events, we put the detector deep underground, where the cosmic rays will not reach it.



Original
Davis et. al.
solar
neutrino
experiment

A tank
containing
615 tons
of
cleaning
fluid

In a gold mine in the US

ν_e from Sun + **Chlorine atom** → e + **Argon atom**

After two months, extract approximately

30 Argon atoms

from the tank, which contains

10,000,000,000,000,000,000,000,000,000,000 atoms.

Count the Argon atoms.

This experiment saw only 1/3 the predicted number of ν_e coming from the Sun.

The possibilities:

The calculations of  et al. were wrong.

The experiment of  et al. was wrong.

Both of them were wrong.

Could it be that ***neither*** of them was wrong?

For decades, Bahcall stuck to his calculated prediction, and Davis stuck to his measured result.

Then —

Several new experiments, especially those of the Sudbury Neutrino Observatory (SNO), showed that both of them had been right.

In a nickel mine
near Sudbury, Canada

The SNO detector

The central sphere is
filled with 1000 tons
of heavy water.

Photo courtesy of SNO

SNO detects solar neutrinos in several different ways.

One way counts ———

$$\text{Number}(\nu_e)\ .$$

Another counts ———

$$\text{Number}(\nu_e) + \text{Number}(\nu_\mu) + \text{Number}(\nu_\tau)\ .$$

SNO finds ———

$$\frac{\text{Number}(\nu_e)}{\text{Number}(\nu_e) + \text{Number}(\nu_\mu) + \text{Number}(\nu_\tau)} = 1/3\ .$$

All the solar neutrinos are born as ν_e .

But 2/3 of them turn into ν_μ or ν_τ, which were invisible to Ray Davis, before they reach earth.

Neutrinos do change flavor.

Therefore, neutrinos do have non-zero masses.

In 2002 —

Nobel Prize to **Ray Davis**

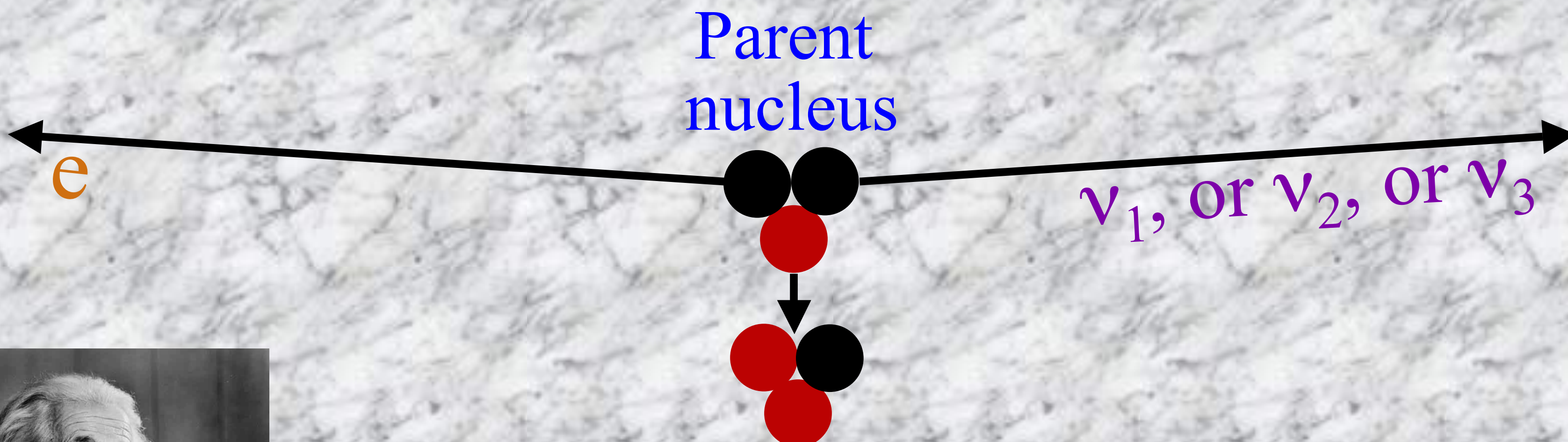
Nobel Prize to **Masatoshi Koshiba**
(Led the creation of key experiments in the Kamioka mine in Japan)

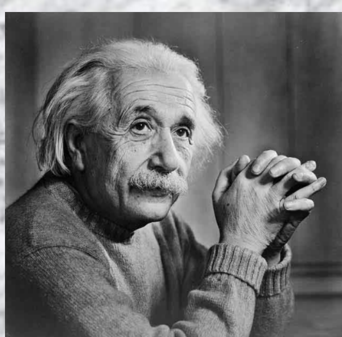
………………………………………………………

Innumerable prizes to **John Bahcall**

Open Questions for Future Experiments

How Much Do the Neutrino Particles ν_1, ν_2, and ν_3 Weigh?





Final Energy of motion = (Initial mass – Final mass) x c^2

The heavier the neutrino is,
the less energy the electron will have.

A good e energy measurement requires a ***BIG*** apparatus.

KATRIN’S JOURNEY

Are Neutrinos Their Own Antiparticles?

For every particle , there is a corresponding antiparticle.

Matter	Different?	Antimatter
Electron	Yes	Positron
Proton	Yes	Antiproton
Neutron	Yes	Antineutron
Photon	No	Antiphoton
Neutrino ν	??	Antineutrino $\bar{\nu}$

Does $\bar{\nu} = \nu$?

Q: Why should we care?

A: Protons and neutrons are made of ***quarks***.

The Large Hadron Collider, near Geneva, is seeking the origin of the masses of the ***quarks*** and the ***charged leptons***.

If $\bar{\nu} = \nu$, then at least a part of the mass of the ***neutrinos*** has a different origin than the masses of the ***quarks*** and the ***charged leptons***.

Probing whether $\bar{\nu} = \nu$ is probing the origin of mass.

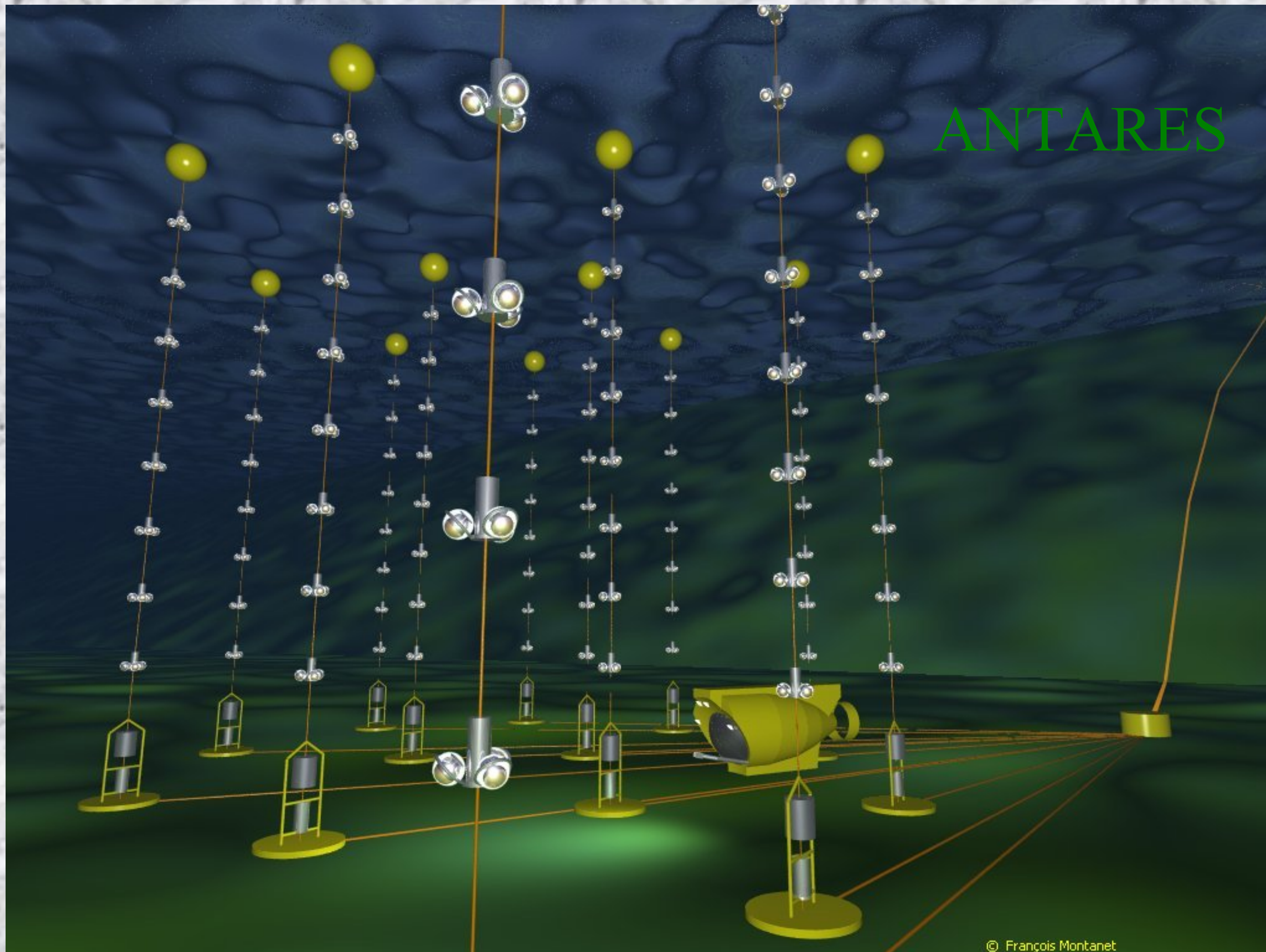
What Can Neutrinos, Acting As Messengers, Tell Us About the Universe?

Neutrinos are very penetrating.

They can reach us
from a distant source when light cannot.

The old way to do astronomy

In the Mediterranean Sea



The new way

Are We the Children of Heavy Neutrinos?

For every particle , there is a corresponding antiparticle.

Matter	Antimatter
Electron	Positron
Proton	Antiproton
Neutron	Antineutron

We humans are made of Matter.

The universe contains Matter,
but almost no Antimatter.

Good thing for us there is no Antimatter around.

Life is possible only because
there is no Antimatter around.

Cosmology:

Just after the Big Bang that started the universe —

There were ***equal*** amounts
of Matter and Antimatter.

Then the present ***difference*** between the amounts of Matter and Antimatter — Matter is present but Antimatter is essentially absent — must have developed after the earliest moments following the Big Bang.

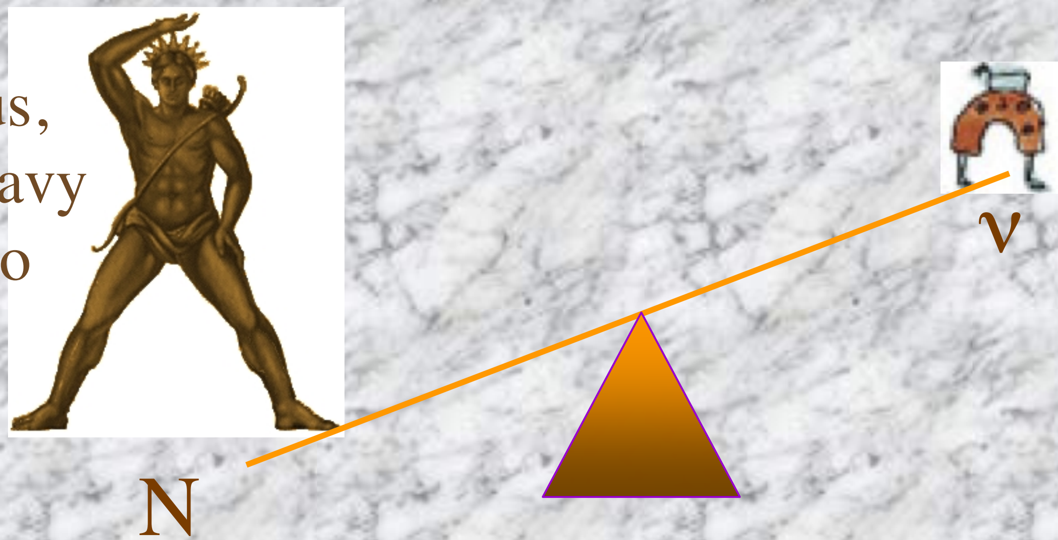
This could not have happened unless
Matter ***and*** Antimatter ***behave differently*.**

A Matter-Dominated Universe From Neutrinos

The neutrinos have masses at least one-million times smaller than the mass of the next lightest particle, the electron.

How can anything weigh that little?

The See-Saw Mechanism

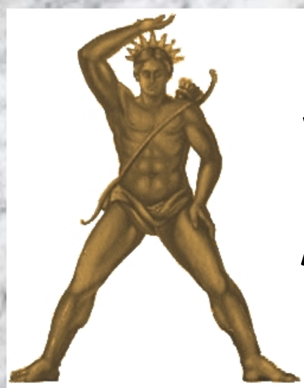


The more the heavy neutrinos N weigh,
the less the light ones ν will weigh.

The heavy neutrinos N decay into other things
after a tiny fraction of a second.

The Children of Collosi

In the *See-Saw* picture, the heavy neutrinos N in the early universe would have decayed according to —



N

or

Electron + …

Positron + …

Neither matter nor antimatter

We expect one of these two alternatives to be more probable than the other.

These decays would have left behind a universe with unequal amounts of **Matter** (the Electrons) and **Antimatter** (the Positrons).

This is exactly what we are trying to explain.

Unequal numbers of Electrons and Positrons

Confidently Expected

Processes

Unequal numbers of Atoms and Anti-atoms

Is This Our History?

The heavy neutrinos N are estimated to weigh about a billion times more than a proton.

No scientific laboratory, presently existing or foreseen, can make anything that heavy.

But the heavy neutrinos N are related to the light ones ν by the See Saw.

We can obtain evidence that we are descended from heavy neutrinos by studying the light ones.

Europe, Japan, and the US are all developing plans for the required studies.

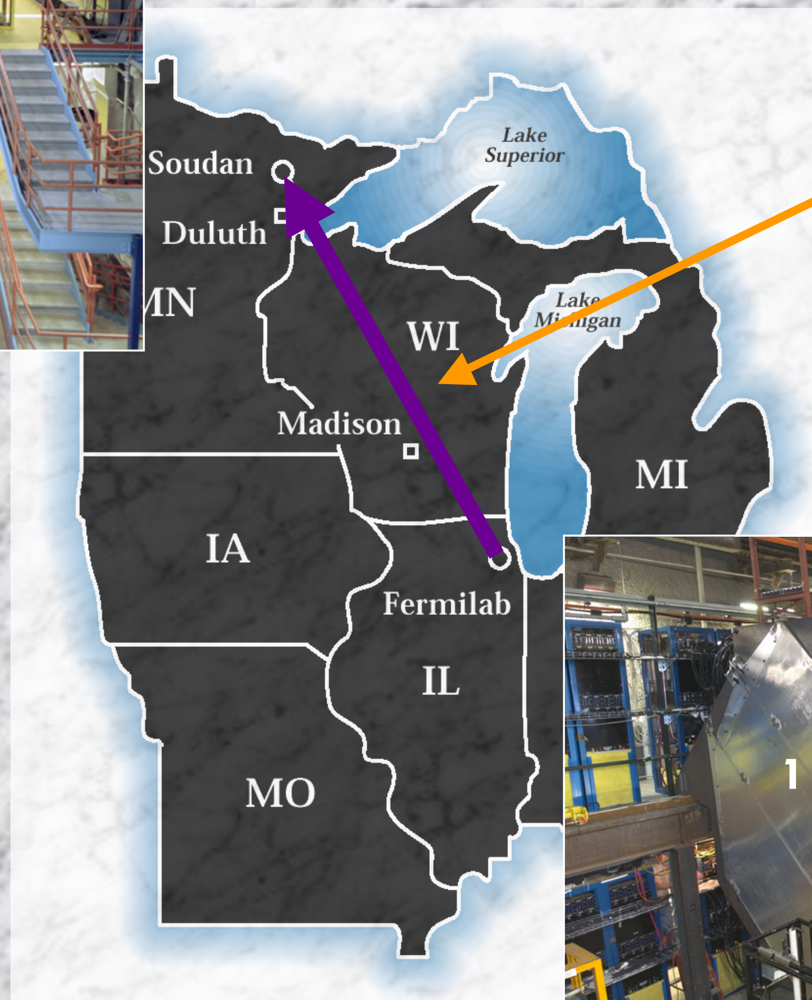
Possibilities in Europe

(From K. Sakashita)

What Surprises Are In Store?

This conference reported several surprises.

The MINOS Experiment



ν or $\bar{\nu}$ beam

From P. Vahle

The Surprise: There is some evidence that, contradicting some very well confirmed theory, $\overline{\nu}_\mu$ disappear into other flavors differently (faster) than ν_μ do.

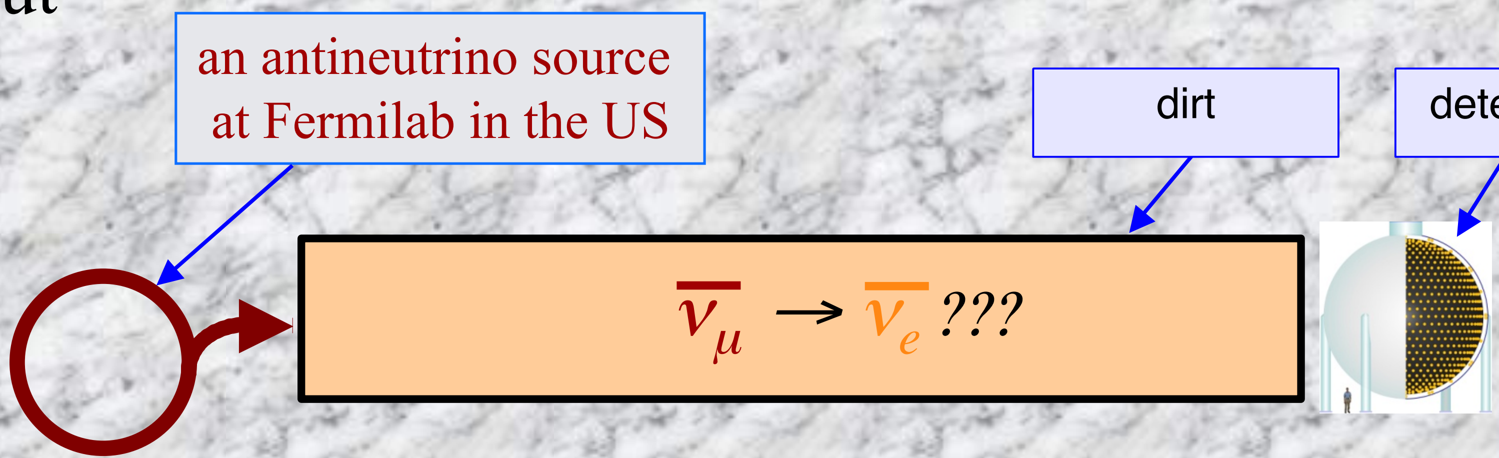
Is this because neutrinos and antineutrinos interact with earth matter differently than we think they do?

The MiniBooNE Experiment

Results from an experiment called LSND
do not fit our otherwise successful picture
of the neutrinos and their properties.

MiniBooNE was designed to confirm or refute LSND.
Results with neutrinos did not confirm LSND.

But —



From R. Van de Water

Surprise: Antineutrino results show unexpected behavior consistent with what LSND saw.

What new surprises are waiting to be discovered?

Summary

Neutrinos are abundant, but elusive.

They have tiny, but nonzero, masses.

They can do amazing things, like change from chocolate- to strawberry-flavored.

Without them, we wouldn’t be here.

They are under our skin—always.